Training event “Atmospheric Remote Sensing observation: labs maintenance and methods”

Raileigh fit test in lidar measurements

Aldo Amodeo

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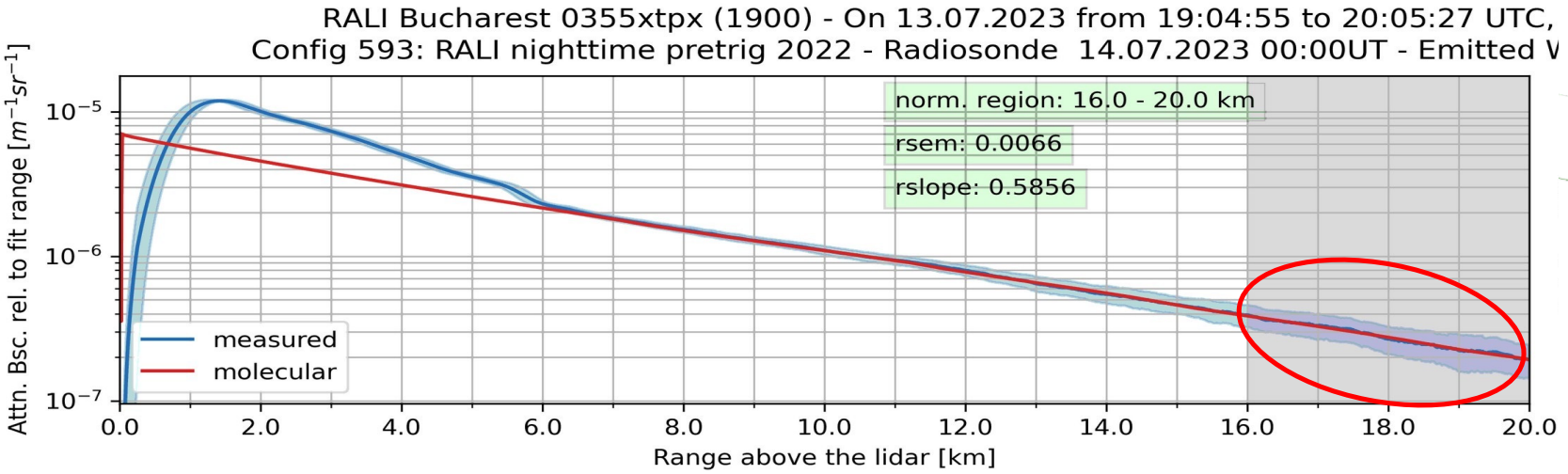
Ministero dell'Università e della Ricerca
Italiadomani

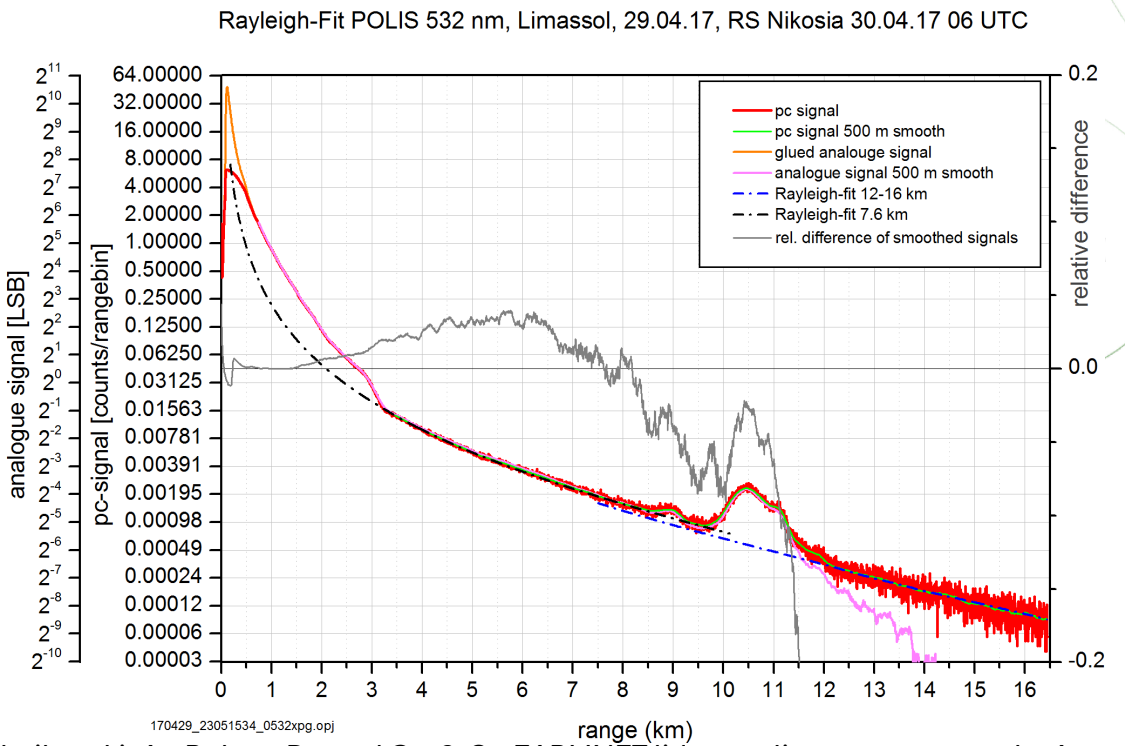
Rayleigh fit test

- **PRINCIPLE:** comparison of lidar signals in clean air ranges with the calculated signals from air density, the Rayleigh (molecular) backscatter is the **only absolute calibration of lidar signals**.
- **METHOD:** in a well-calibrated LiDAR system, the measured backscatter profile from the atmosphere at high altitudes (where aerosol contribution is minimal) should **match (be "fitted" by) the theoretical Rayleigh profile**.
- **ANY DEVIATION** from this expected profile can indicate calibration errors, optical misalignment, or system performance issues.



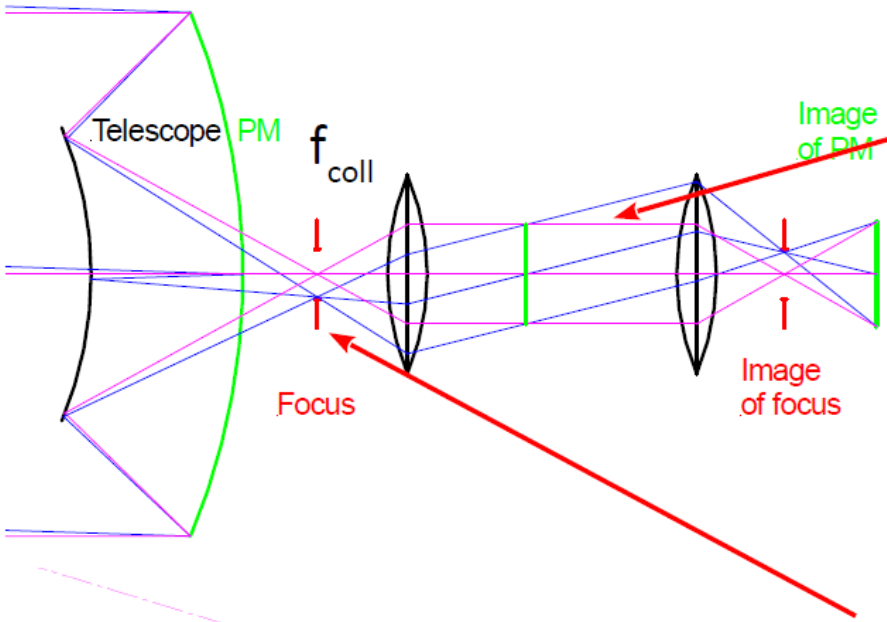
Characteristics of the lidar signal and consequences

High dynamic range. It spans within several order of magnitudes. The high dynamic range of near to far range signals can cause a too high signal-to-noise ratio or signal distortions in the far range (analogue signals) with uncertainty in the Rayleigh calibration and/or overload of the signal in the near range (photon counting saturation).

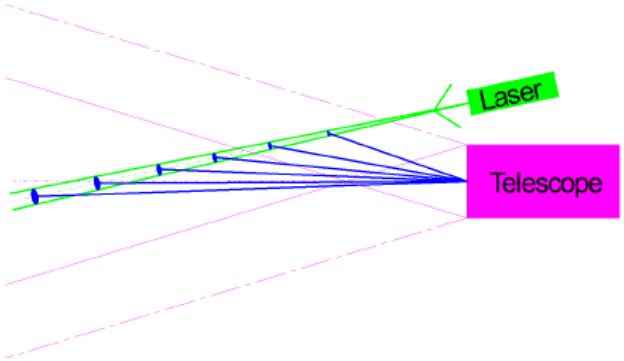


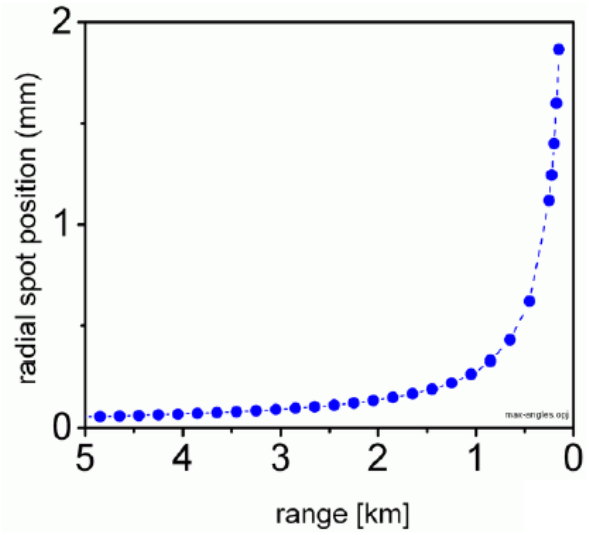
see: Freudenthaler, V., Linné, H., Chaikovski, A., Rabus, D., and Groß, S.: EARLINET lidar quality assurance tools, Atmos. Meas. Tech. Discuss. [preprint], https://doi.org/10.5194/amt-2017-395, in review, 2018.

Receiver optics – light paths and angles



$(\tan)\ \beta = x / f_{coll}$





see: ACTRIS – CARS webinar 07.02.23 Volker Freudenthaler, QA/QC test measurements

Lidar equation

Elastic backscattering

$$P(\lambda_L, r) = P_L \frac{c\tau_d}{2} \chi(r) \frac{A}{r^2} \zeta(\lambda_L) \beta(\lambda_L, r) \exp\left(-2 \int_0^r \alpha(\lambda_L, r') dr' \right)$$

Raman backscattering

$$P(\lambda, \lambda_L, r) = P_L \frac{c\tau_d}{2} \chi(r) \frac{A}{r^2} \zeta(\lambda) \beta(\lambda, \lambda_L, r) \exp\left(- \int_0^r \alpha(\lambda_L, r') dr' \right) \exp\left(- \int_0^r \alpha(\lambda, r') dr' \right)$$

P(λ,r) light power measured from range *r* at wavelengh λ
λ_L laser wavelength, λ Raman wavelength
A receiver effective area
P_L laser transmitted power
c light speed, τ_d dwell time
$\chi(r)$ overlap function, $\chi(r)$ = 1 above full overlap altitude
$\zeta(\lambda)$ efficiency (receiver, detection) at a wavelength λ
β backscatter coefficient at a wavelength (sum of molecules and aerosol contributions)
α extinction coefficient at a wavelength (sum of molecules and aerosol contributions)

Lidar equation

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β backscatter coefficient at a wavelength (sum of molecules and aerosol contributions)
α extinction coefficient at a wavelength (sum of molecules and aerosol contributions)

In the far range, all factors in red are constant

The theory

$$r^2 P(\lambda_L, r) = C\left(\beta_m(\lambda_L, r) + \beta_p(\lambda_L, r)\right)\exp\left[-2\int_0^r \left(\alpha_m(\lambda_L, r') + +\alpha_p(\lambda_L, r')\right) dr'\right]$$ measured range corrected elastic lidar signal

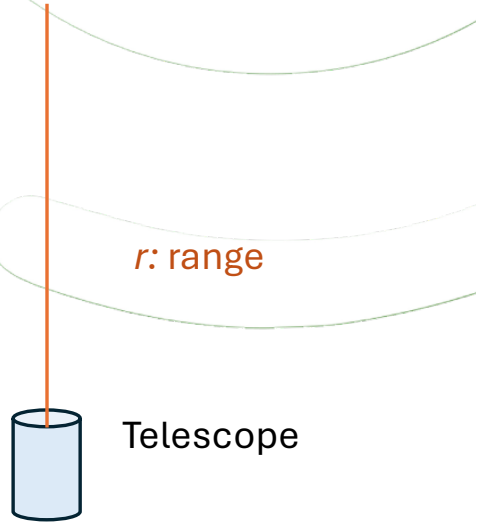
$$\beta_m^{att}(\lambda_L, r) = \beta_m(\lambda_L, r)\exp\left[-2\int_0^r \alpha_m(\lambda_L, r')\, dr'\right]$$ attenuated molecular backscatter coefficient

In the far range, in aerosol free conditions for a generic wavelength λ:

$$\frac{r^2 P(\lambda, r)}{C} = \beta_m^{att}(\lambda, r)$$

$$\beta_m(\lambda, r) = B_S(\lambda)\frac{p(r)}{T(r)}$$ molecular backscatter

$$\alpha_m(\lambda, r) = \frac{8\pi}{3} k_{bw}\beta_m(\lambda, r)$$ molecular extinction



pressure *p*, temperature *T* , range *r*, height *z*, constants B_s, k_{bw}, *C*

The theory

$$r^2 P(\lambda_L, r) = C\left(\beta_m(\lambda_L, r) + \beta_p(\lambda_L, r)\right)\exp\left[-2\int_0^r \left(\alpha_m(\lambda_L, r') + +\alpha_p(\lambda_L, r')\right) dr'\right]$$ measured range corrected elastic lidar signal

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In the far range, in aerosol free conditions for a generic wavelength λ:

$$\frac{r^2 P(\lambda, r)}{C} = \beta_m^{att}(\lambda, r)$$

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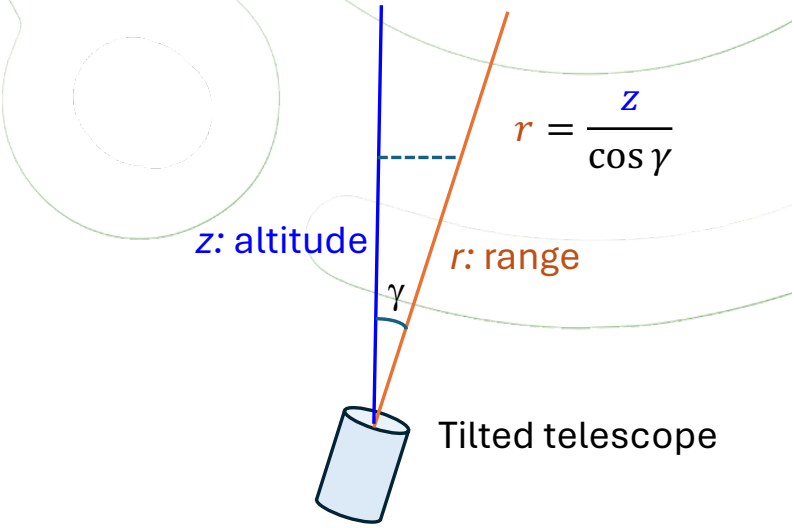

pressure *p*, temperature *T* , range *r*, height *z*, constants B_s, k_{bw}, *C*

How to calculate the molecular attenuated backscatter signal/1

Pressure and temperature profiles can be obtained from radiosondes or models.

$$\beta_m(\lambda, z) = B_S(\lambda)\frac{p(z)}{T(z)}$$

molecular backscatter

$$\beta_m(\lambda, z) = N(z)\sigma_R(\lambda)$$

$\sigma_R(\lambda)$ is the total Rayleigh scattering cross section per molecule

A. Bucholtz, "Rayleigh-scattering calculations for the terrestrial atmosphere," Appl. Opt. 34, 2765-2773 (1995)

Wynn L. Eberhard, "Correct equations and common approximations for calculating Rayleigh scatter in pure gases and mixtures and evaluation of differences," Appl. Opt. 49, 1116-1130 (2010)

$$\sigma_R(\lambda) = \frac{24\pi^3}{N_s^2 \lambda^4} \left(\frac{n_\lambda^2 - 1}{n_\lambda^2 + 2} \right)^2 \frac{6 + 3\rho_n(\lambda)}{6 - 7\rho_n(\lambda)}$$

λ [nm]	ρ_n
355	0.03010
532	0.02842
1064	0.02730

- $\rho_n(\lambda)$: depolarization factor, due to the anisotropy of the air molecules
- N_s molecular number density for standard air (2.54743 x 10^{19} cm^{-3})
- n_λ refractive index for standard air at λ

$$(n_\lambda - 1) \times 10^8 = \frac{5791817}{238.0185 - (1/\lambda)^2} + \frac{167909}{57.362 - (1/\lambda)^2} \qquad \lambda > 230nm$$

$$(n_\lambda - 1) \times 10^8 = 8060.51 + \frac{2480990}{132.274 - (1/\lambda)^2} + \frac{17455.7}{39.32957 - (1/\lambda)^2} \qquad \lambda \leq 230nm$$

A. Bucholtz, *Rayleigh-scattering calculations for the terrestrial atmosphere*, **Appl. Opt. Vol. 34, N. 15**, pp. 2765-2773 (1995)
R. Miles at al, *Laser Rayleigh scattering*, **Meas. Sci. Technol. , 12**, R33-R51 (2001)

Where atmospheric models can be found?

Cloudnet (https://cloudnet.fmi.fi/) provides models for a station:

- **directly** through website GUI in case of a CloudNet station
- **through API** for all the stations registered to the SCC, selecting the model or all the available models for the station:

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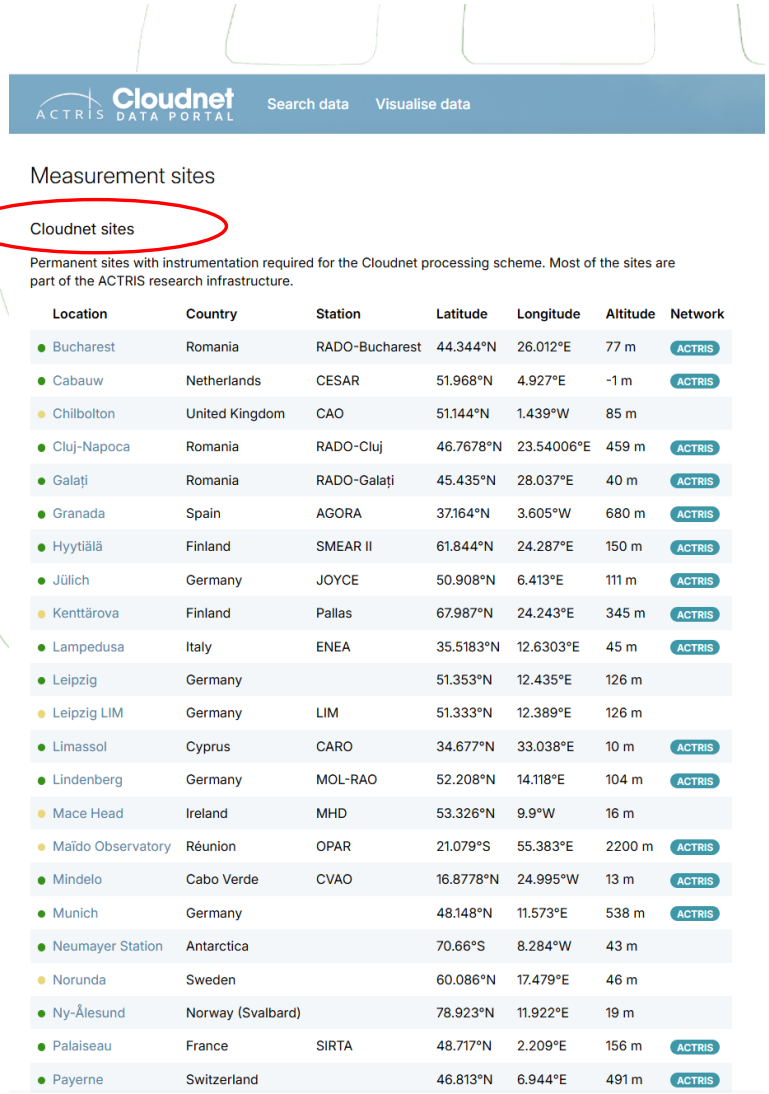

Location	Country	Station	Latitude	Longitude	Altitude	Network
Bucharest	Romania	RADO-Bucharest	44.344°N	26.012°E	77 m	ACTRIS
Cabauw	Netherlands	CESAR	51.968°N	4.927°E	-1 m	ACTRIS
Chilbolton	United Kingdom	CAO	51.144°N	1.439°W	85 m	
Cluj-Napoca	Romania	RADO-Cluj	46.7678°N	23.54006°E	459 m	ACTRIS
Galați	Romania	RADO-Galați	45.435°N	28.037°E	40 m	ACTRIS
Granada	Spain	AGORA	37.164°N	3.605°W	680 m	ACTRIS
Hyytiälä	Finland	SMEAR II	61.844°N	24.287°E	150 m	ACTRIS
Jülich	Germany	JOYCE	50.908°N	6.413°E	111 m	ACTRIS
Kenttärova	Finland	Pallas	67.987°N	24.243°E	345 m	ACTRIS
Lampedusa	Italy	ENEA	35.5183°N	12.6303°E	45 m	ACTRIS
Leipzig	Germany		51.353°N	12.435°E	126 m	
Leipzig LIM	Germany	LIM	51.333°N	12.389°E	126 m	
Limassol	Cyprus	CARO	34.677°N	33.038°E	10 m	ACTRIS
Lindenberg	Germany	MOL-RAO	52.208°N	14.118°E	104 m	ACTRIS
Mace Head	Ireland	MHD	53.326°N	9.9°W	16 m	
Maïdo Observatory	Réunion	OPAR	21.079°S	55.383°E	2200 m	ACTRIS
Mindelo	Cabo Verde	CVAO	16.8778°N	24.995°W	13 m	ACTRIS
Munich	Germany		48.148°N	11.573°E	538 m	ACTRIS
Neumayer Station	Antarctica		70.66°S	8.284°W	43 m	
Norunda	Sweden		60.086°N	17.479°E	46 m	
Ny-Ålesund	Norway (Svalbard)		78.923°N	11.922°E	19 m	
Palaiseau	France	SIRTA	48.717°N	2.209°E	156 m	ACTRIS
Payerne	Switzerland		46.813°N	6.944°E	491 m	ACTRIS

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Model sites

Sites with only model data.

Location	Country	Station	Latitude	Longitude	Altitude	Network
Andenes	Norway		69.2783°N	16.009°E	380 m	
Antikythera	Greece	PANGEA	35.86°N	23.31°E	193 m	
Athens	Greece		37.96°N	23.78°E	212 m	
Barcelona	Spain		41.393°N	2.12°E	115 m	
Belgrade	Serbia		44.856°N	20.391°E	89 m	
Belsk	Poland		51.83°N	20.78°E	180 m	
Bilthoven	Netherlands		52.1°N	5.18°E	2 m	
Burjassot	Spain		39.5°N	0.42°W	89 m	
Catania	Italy		37.51°N	15.08°E	190 m	
Clermont-Ferrand	France		45.761°N	3.111°E	420 m	
Cork	Ireland		51.893°N	8.494°W	75 m	
Dushanbe	Tajikistan		38.5594°N	68.8561°E	864 m	
Garmisch-Partenkirchen	Germany		47.477°N	11.064°E	730 m	
Hohenpeissenberg	Germany		47.8019°N	11.0119°E	974 m	
Ispra	Italy		45.817°N	8.617°E	209 m	
Košetice	Czechia	NAOK	49.573°N	15.081°E	531 m	
L'Aquila	Italy		42.344°N	13.327°E	683 m	
Lecce	Italy		40.333°N	18.1°E	30 m	
Lille	France		50.6117°N	3.1417°E	60 m	
Madrid	Spain		40.457°N	3.726°W	669 m	
Manaus	Brazil		2.89°S	59.97°W	109 m	
Minsk	Belarus		53.917°N	27.605°E	200 m	
Naples	Italy		40.838°N	14.183°E	118 m	
Neuchâtel	Switzerland		47.002°N	6.955°E	487 m	
Nicolosi	Italy		37.69°N	14.97°E	1740 m	
Nicosia	Cyprus		35.141°N	33.381°E	180 m	
Rio de Janeiro	Brazil		5.842°S	35.199°W	46 m	

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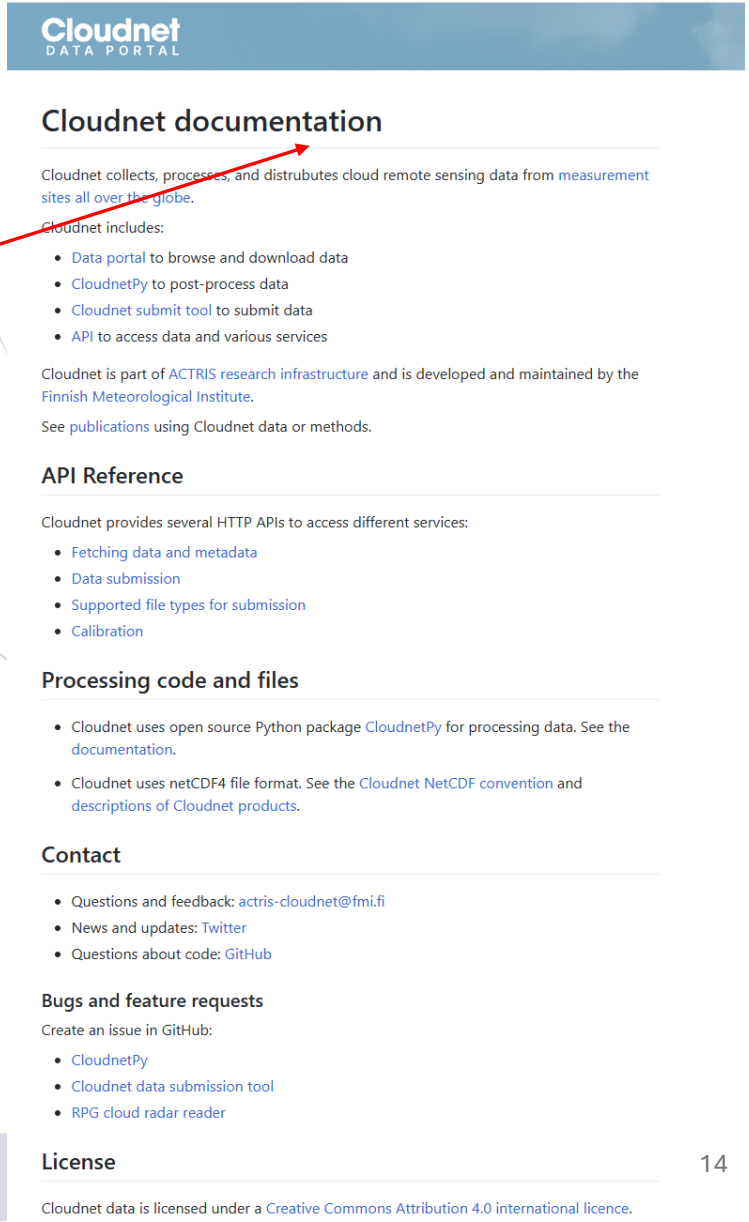
Documentation at: https://docs.cloudnet.fmi.fi/api/data-portal.html



Cloudnet
DATA PORTAL

Cloudnet documentation

Cloudnet collects, processes, and distrubutes cloud remote sensing data from measurement sites all over the globe.

Cloudnet includes:

- Data portal to browse and download data
- CloudnetPy to post-process data
- Cloudnet submit tool to submit data
- API to access data and various services

Cloudnet is part of ACTRIS research infrastructure and is developed and maintained by the Finnish Meteorological Institute.

See publications using Cloudnet data or methods.

API Reference

Cloudnet provides several HTTP APIs to access different services:

- Fetching data and metadata
- Data submission
- Supported file types for submission
- Calibration

Processing code and files

- Cloudnet uses open source Python package CloudnetPy for processing data. See the documentation.
- Cloudnet uses netCDF4 file format. See the Cloudnet NetCDF convention and descriptions of Cloudnet products.

Contact

- Questions and feedback: actris-cloudnet@fmi.fi
- News and updates: Twitter
- Questions about code: GitHub

Bugs and feature requests

Create an issue in GitHub:

- CloudnetPy
- Cloudnet data submission tool
- RPG cloud radar reader

License

Cloudnet data is licensed under a Creative Commons Attribution 4.0 international licence.

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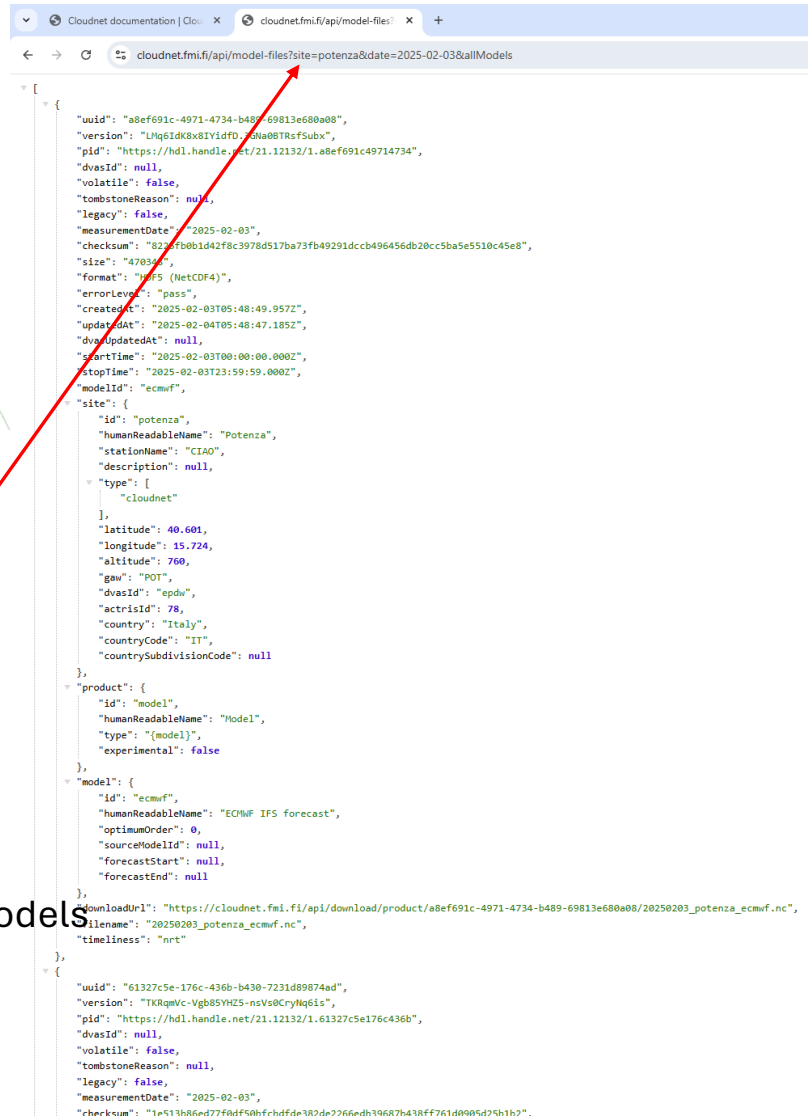


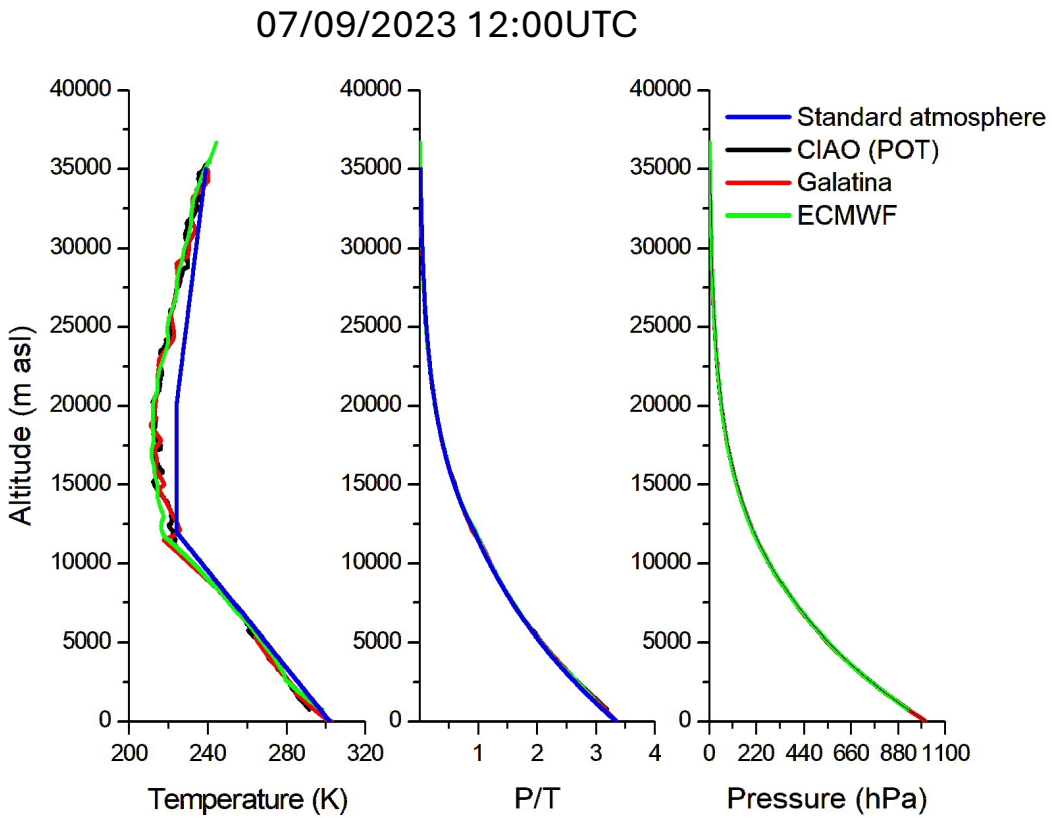
Examples:

https://cloudnet.fmi.fi/api/model-files?site=potenza&date=2025-02-03&allModels

https://cloudnet.fmi.fi/api/model-files?site=lindenberg&date=2021-02-03&model=gdas1

How to calculate the molecular attenuated backscatter signal

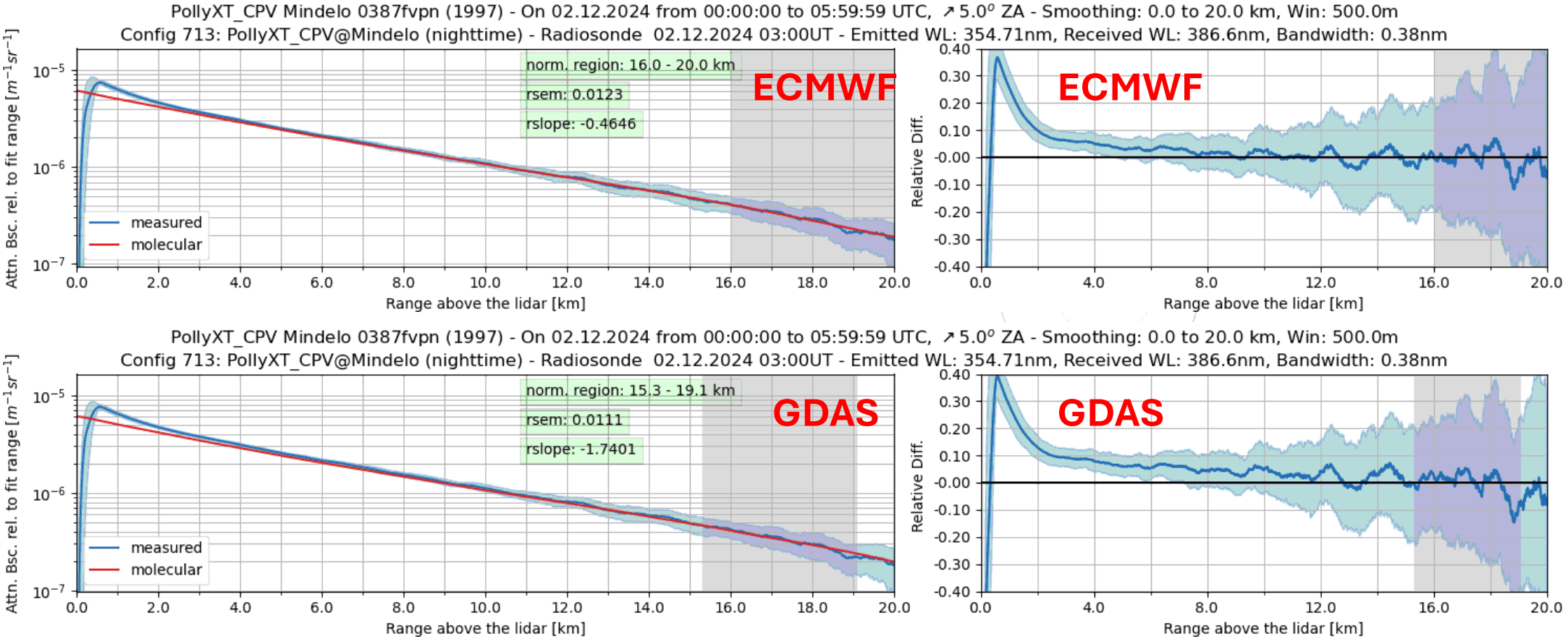
Pressure and temperature profiles can be obtained from **radiosondes or models**.



Comparison between p and T profiles obtained from radiosoundings on site at CIAO (Potenza), radiosounding at Galatina (Lecce), 100km far, ECMWF forecast model, Standard atmosphere.

387 far-range

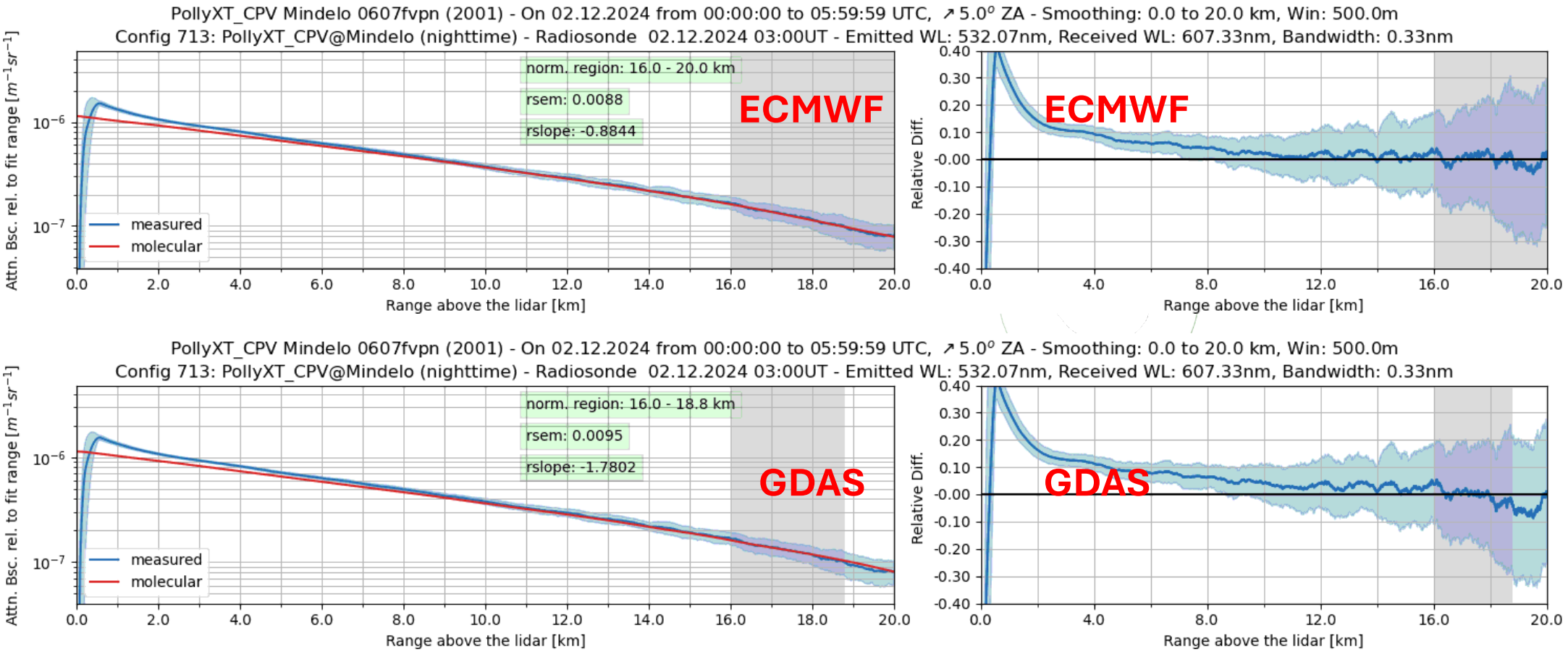
Effect of the of the model



Provided by Julian Hofer (Tropos) and Nikolaos Siomos (LMU)

607 far-range

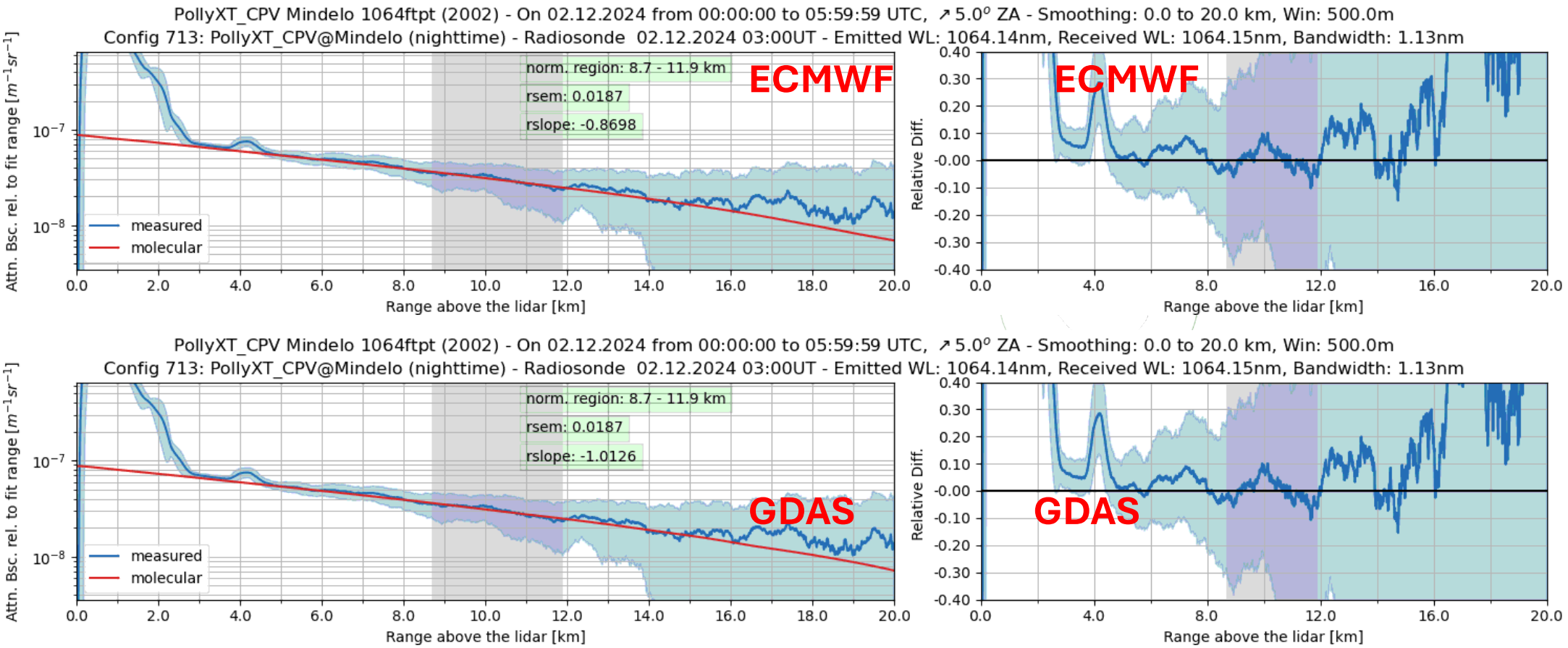
Effect of the of the model



Provided by Julian Hofer (Tropos) and Nikolaos Siomos (LMU)

1064 far-range

Effect of the of the model



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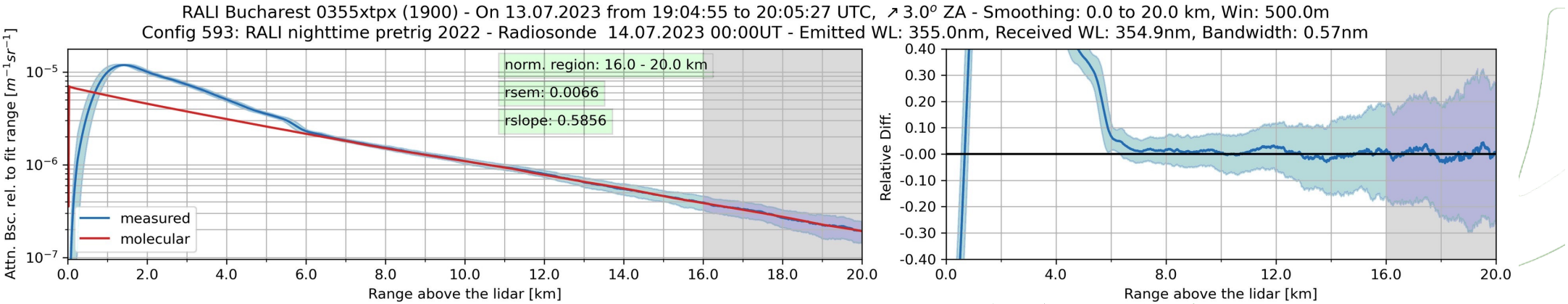
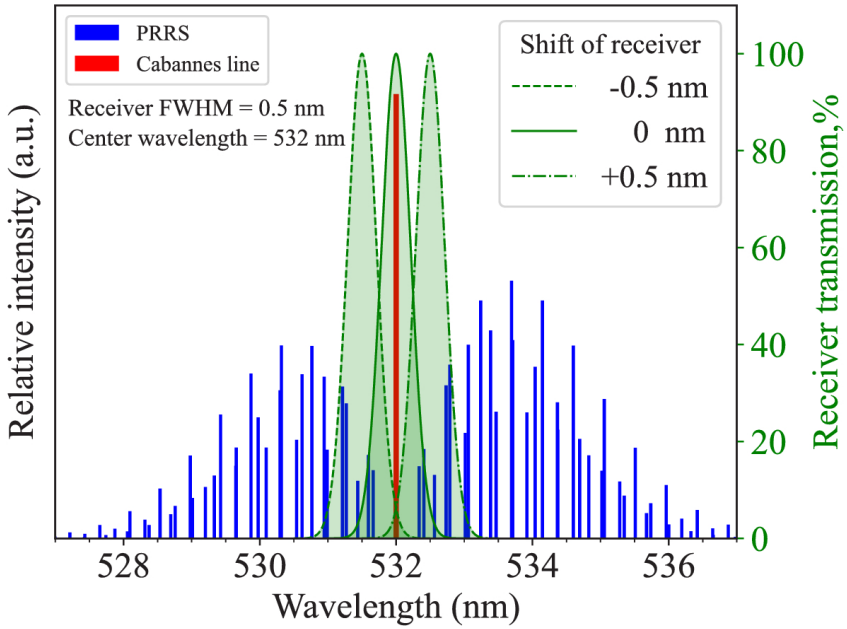


rsem: relative standard error of the mean of the residuals between the normalized range-corrected signal and the molecular attenuated backscatter calculated inside the normalization range

rslope: slope of the residuals between the normalized range-corrected signal and the molecular attenuated backscatter calculated inside the normalization range divided by its corresponding error

How to calculate the molecular attenuated backscatter signal

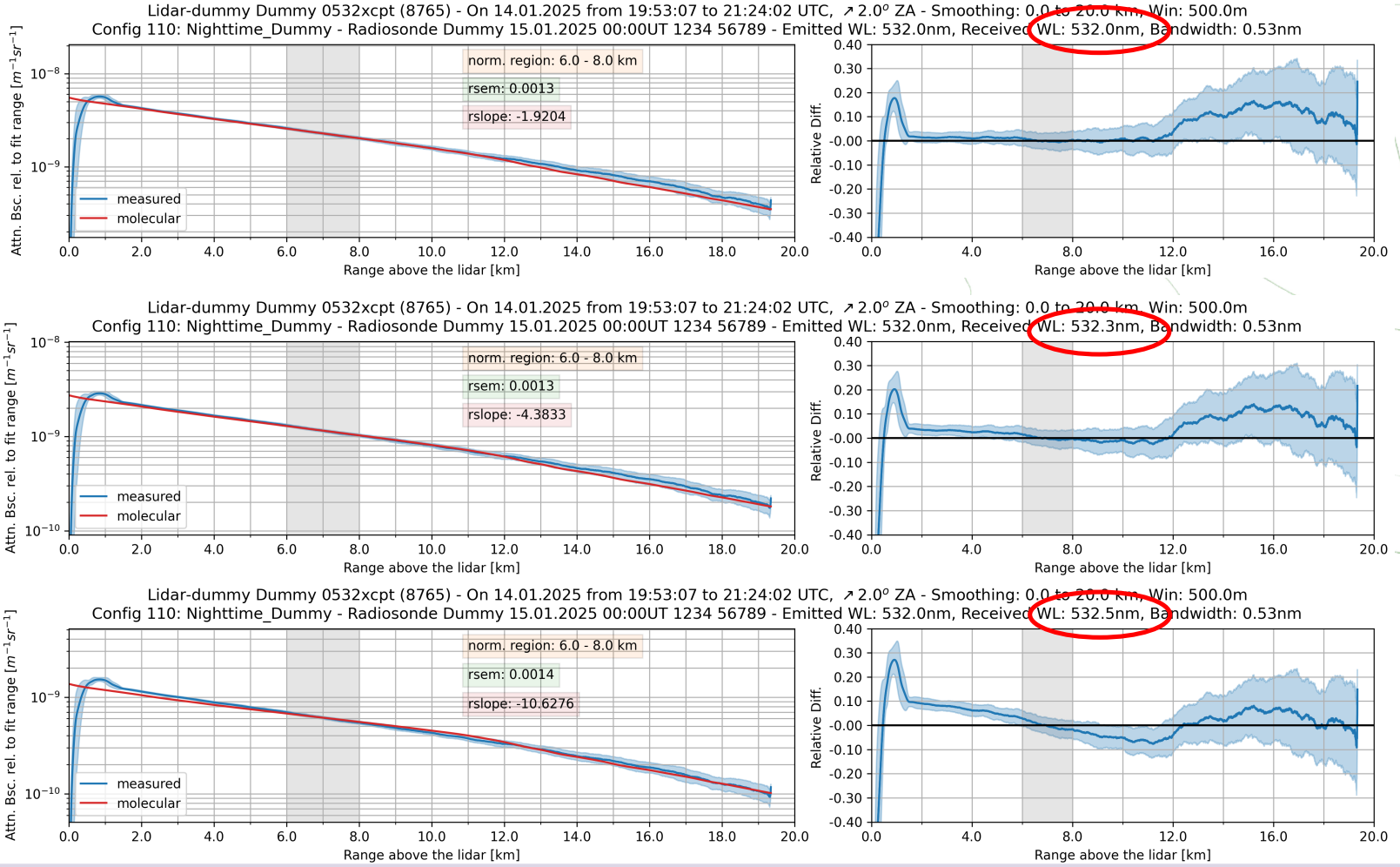
The molecular attenuated backscatter can be related or not only to the Cabannes line, **depending on the Interferential Filter** bandwidth and central wavelength.



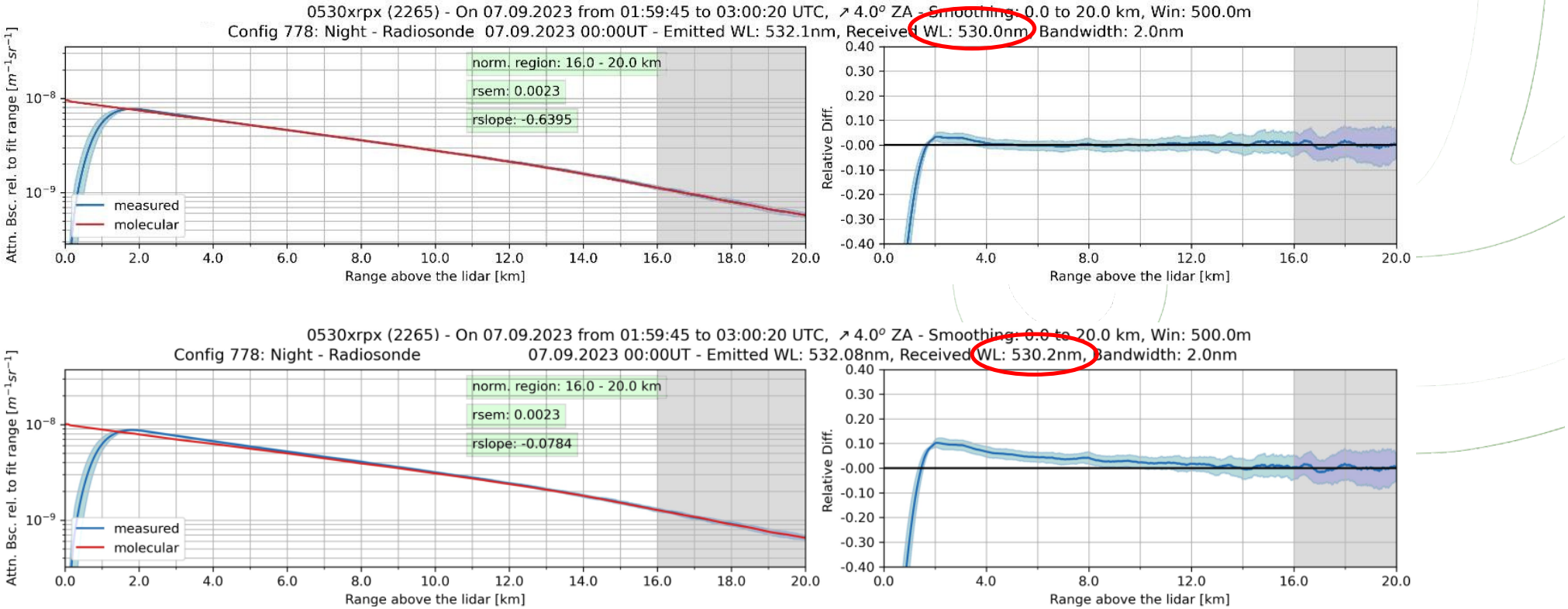
Transmittance curve of a Gaussian-shape filter with a receiving bandwidth of 0.5 nm (FWHM) for different wavelength-shifts (e.g., -0.5 nm, 0 nm, 0.5 nm) in respect to the laser wavelength of 532 nm

Fig. from Z. Kong et al., Opt. Express 31, 24897-24913 (2023)

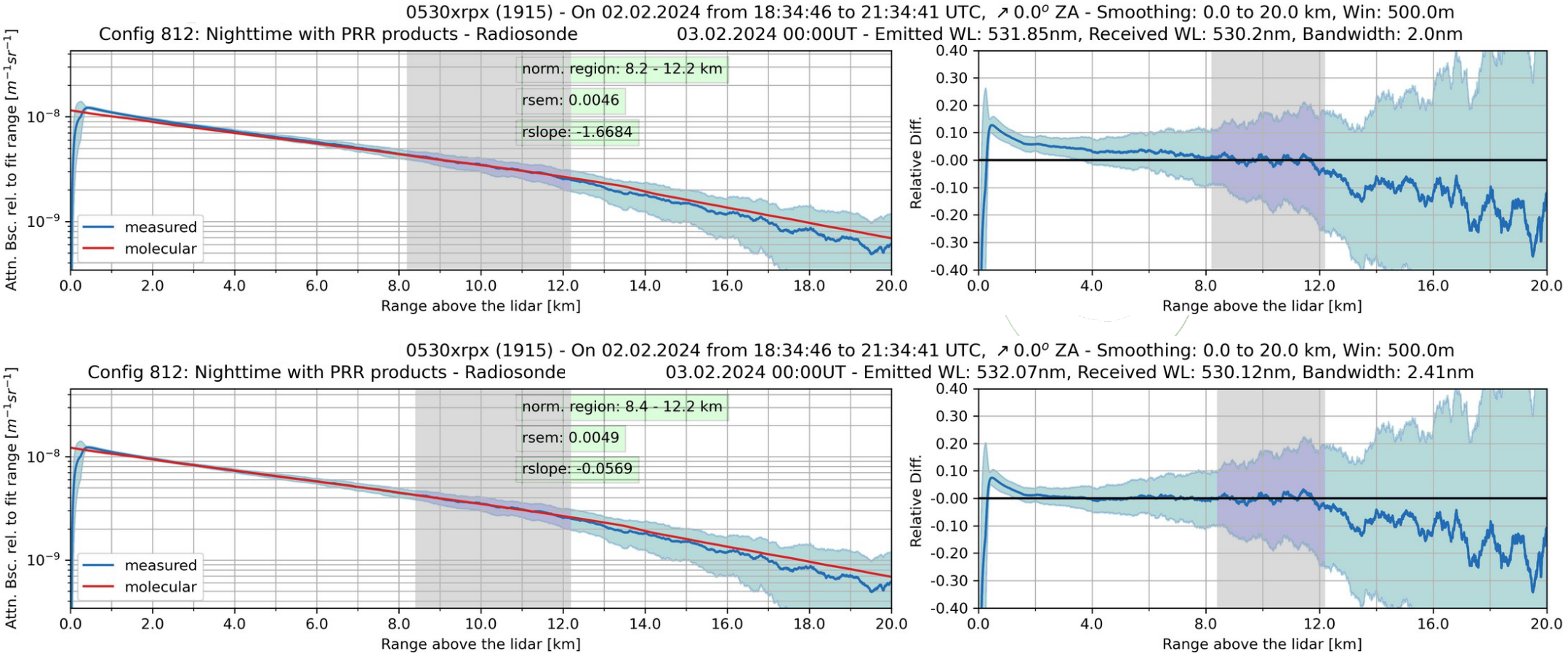
Effect of the of the IF central wavelength



Effect of the of the IF central wavelength



Effect of the of the emitted wavelength, IF central wavelength and IF bandwidth

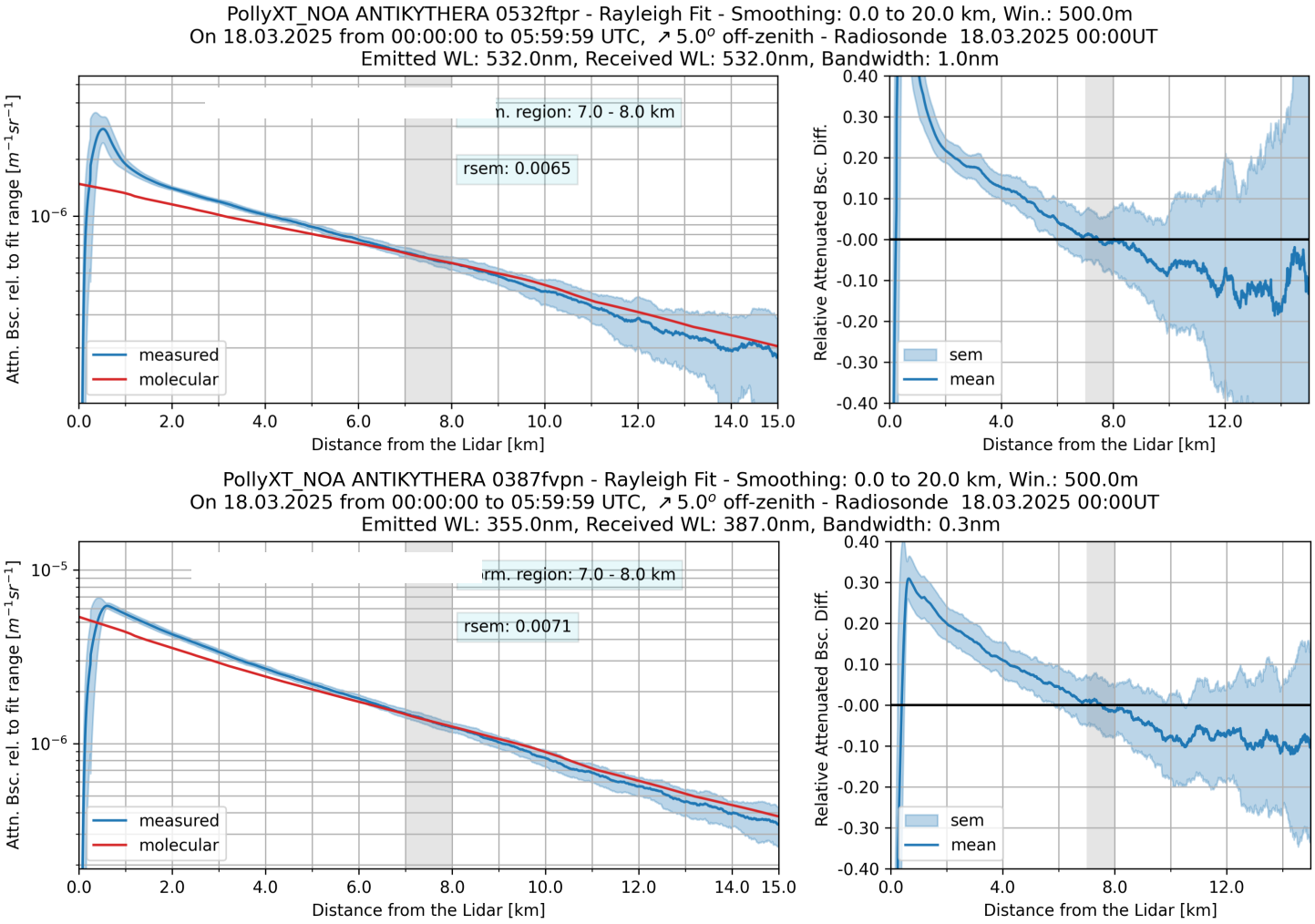


Which information can provide the Rayleigh fit test?

The Rayleigh-fit test provides a check for the far range accuracy measurements:
In particular:

- **Misalignment** of the laser beam
- **Distortions** in the analogue signal
- **Errors**: wrong background subtraction, too high discriminator level setting of the photon counters, and differences in the receiver optics. This can be obtained from the comparison of the signals at different wavelengths.
- **Maximum channel height** (connection with the max product height in the SCC)

Rayleigh fit test: How does misaligned case looks like?



Rayleigh fit test:

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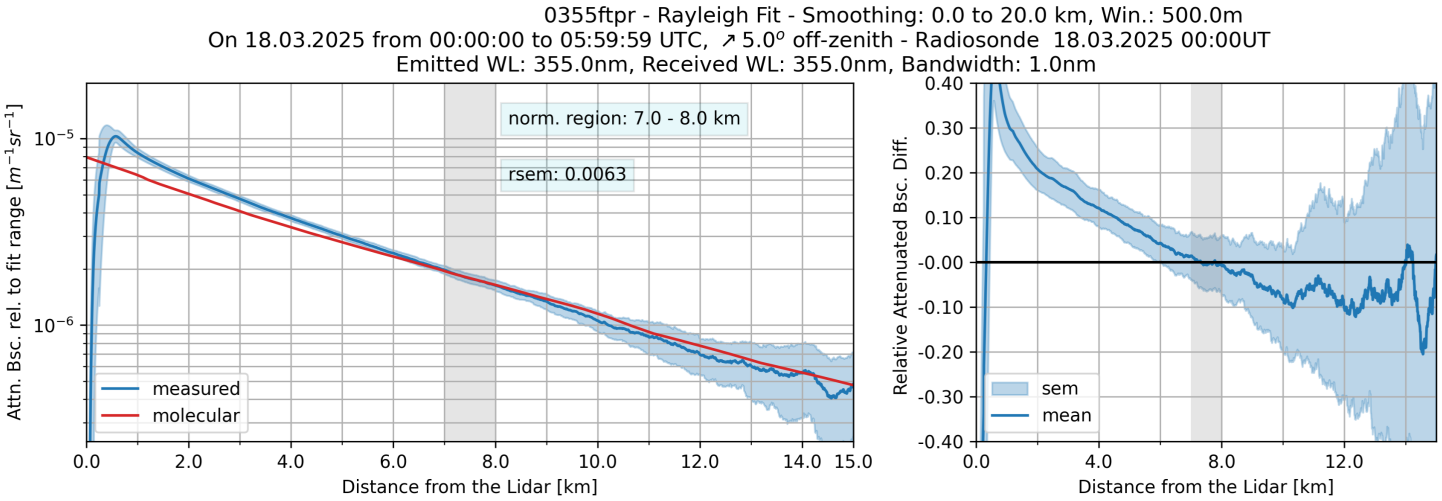

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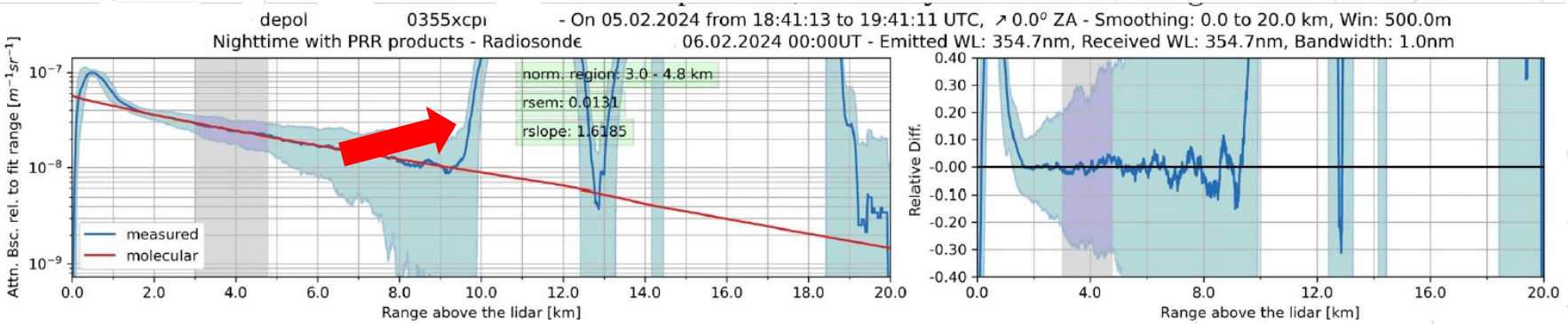
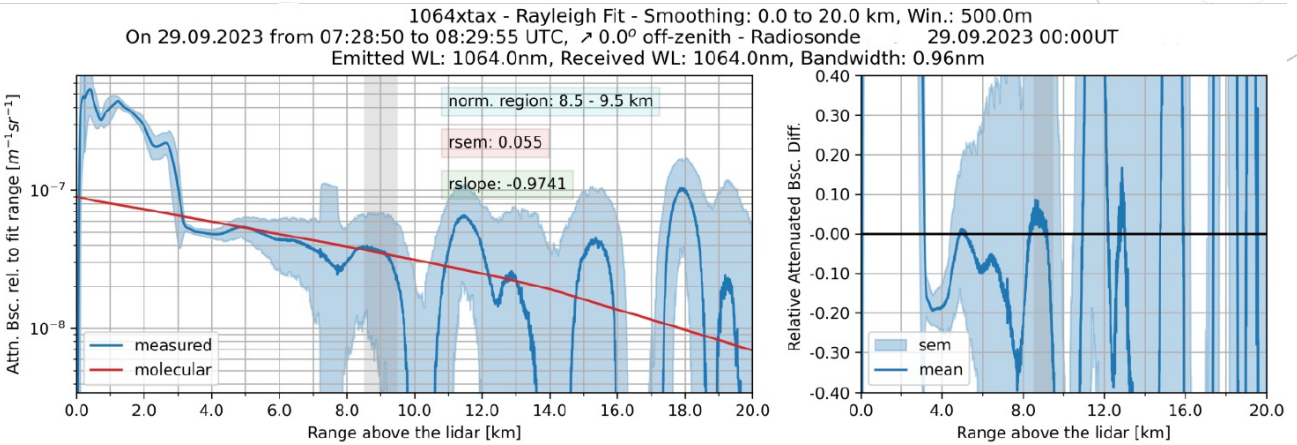
Signal distortions

355xcpr



➔ Signal distortions above 9 km, no clouds (photon channel)

1064xtax



From Michael Haimerl presentation, ACTRIS Week 2024, CARS-ARES Workshop

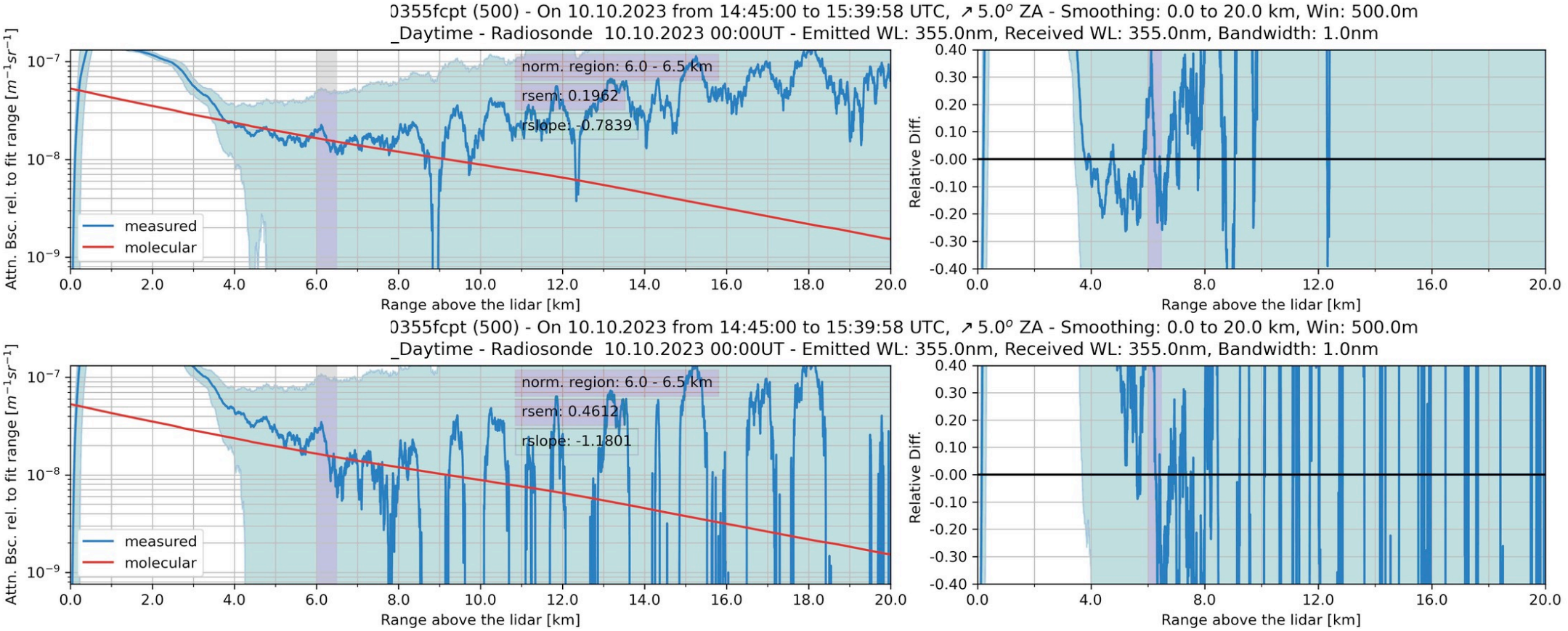
➔ Significant electronic distortions

Which information can provide the Rayleigh fit test?

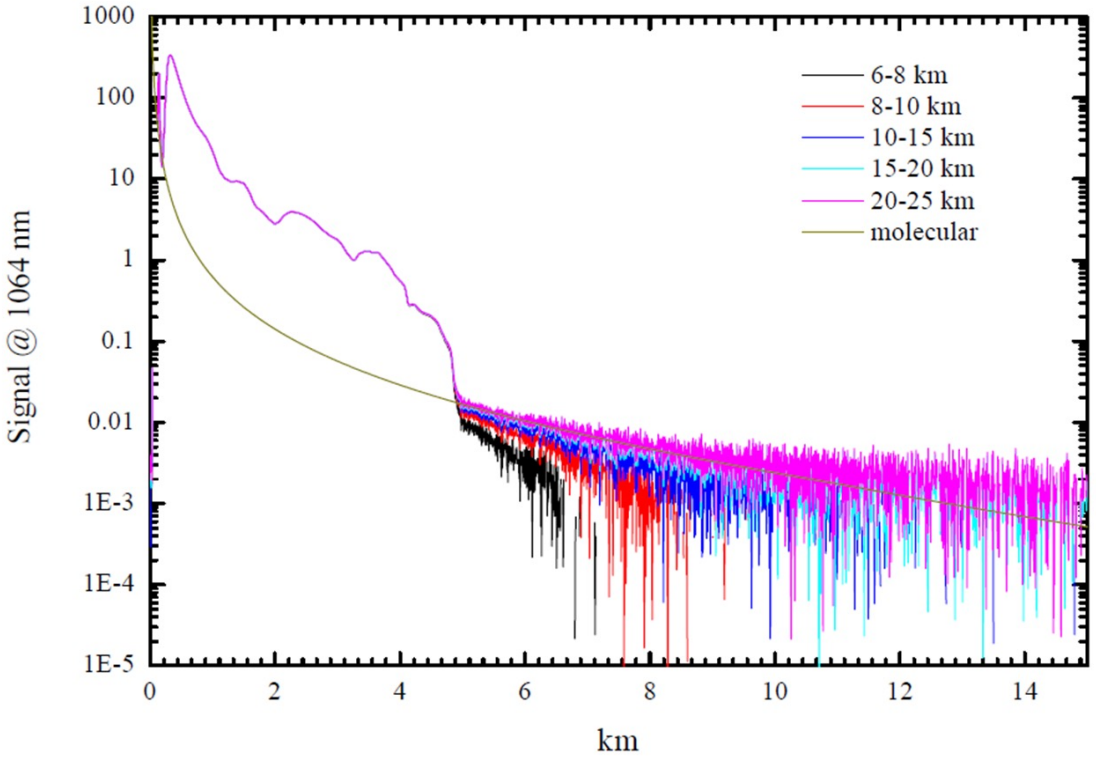
The Rayleigh-fit test provides a check for the far range accuracy measurements:
In particular:

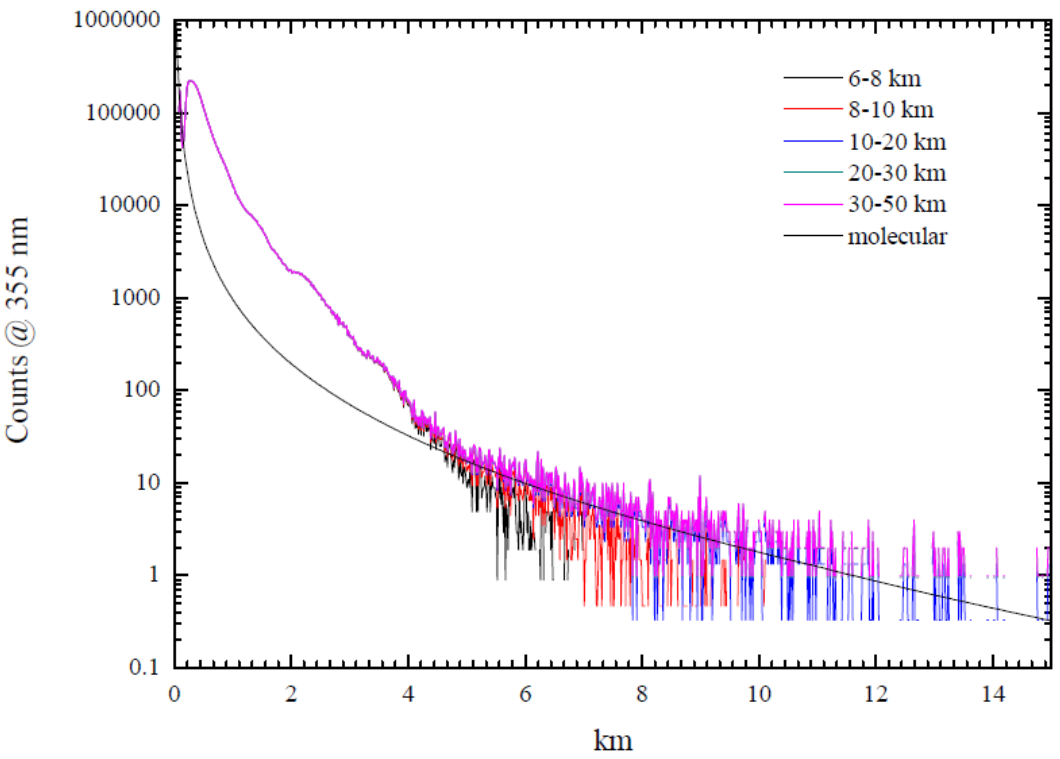
- **Misalignment** of the laser beam
- **Distortions** in the analogue signal
- **Errors**: wrong background subtraction, too high discriminator level setting of the photon counters, and differences in the receiver optics. This can be obtained from the comparison of the signals at different wavelengths.
- **Maximum channel height** (connection with the max product height in the SCC)

Problems in background subtraction



Problems in background subtraction





From Giuseppe D'Amico Training course on Preprocessing, Thessaloniki 2008

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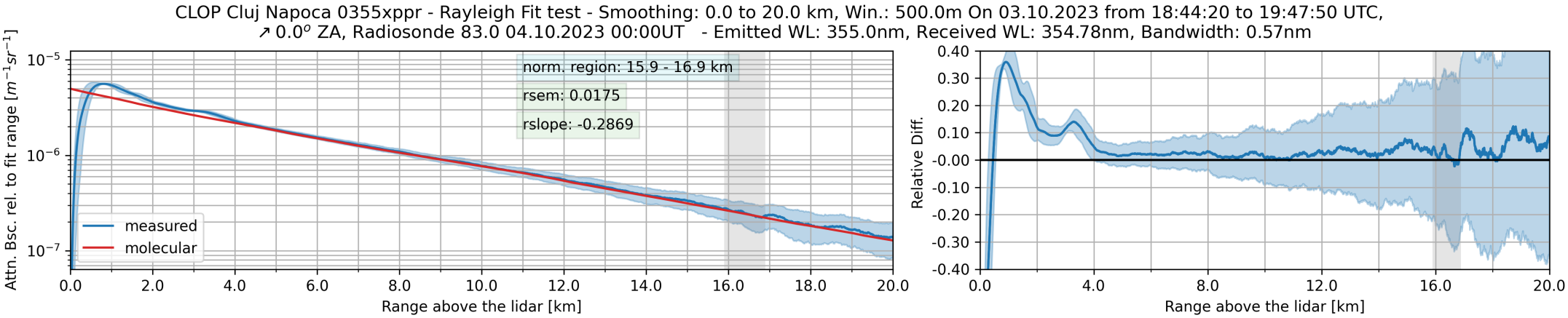
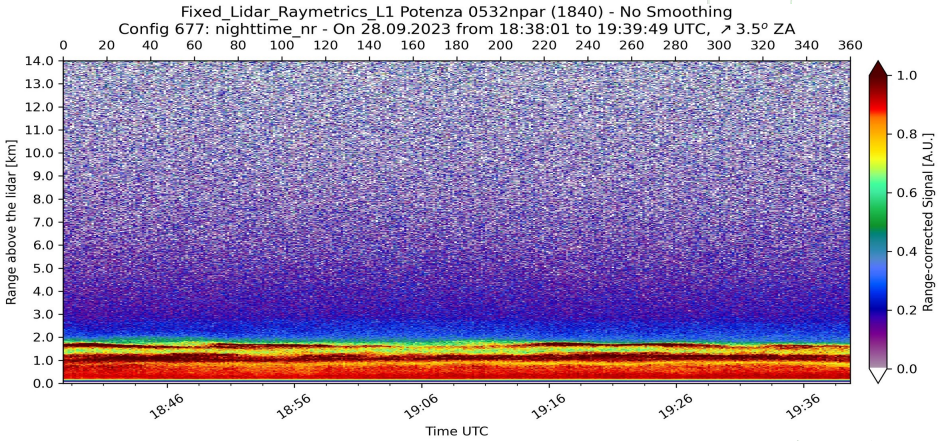


How to perform the Rayleigh fit test

- Extended normal lidar measurement performed in **clear atmospheric conditions and without cirrus clouds**.
- **Conditions must not change** (daytime/nighttime)
- Same lidar **setup as for normal measuring conditions**.
- **Sufficiently long** to improve SNR: at least 1 h measurement (recommended 10 seconds/profile).
- **In case of polarization channels**, useful collect the Rayleigh signal in the calibration mode position (either +45° or -45°) to compare the two signals during the test analysis and to reduce the atmospheric variability.
- **Dark signal** before each test for all analogue channels (5-10 min as a general rule)
- **Radiosonde data or model data** must be provided.
- Use the **far range signal** (PC if analog and PC are glued, analog if the only available)

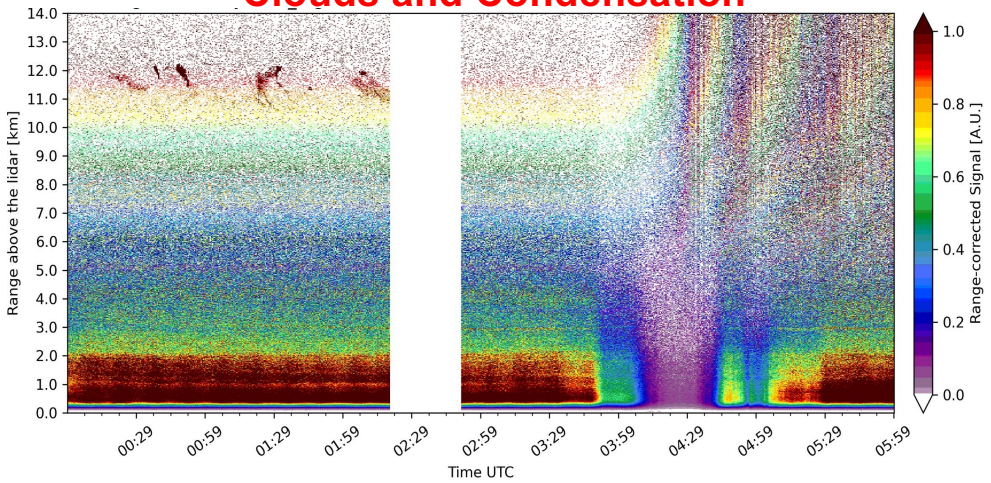
See: *High Power Lidar: Standard Quality Assurance Procedures for NF operations* at https://www.actris.eu/topical-centre/cars/announcements-resources/documents

A typical good test

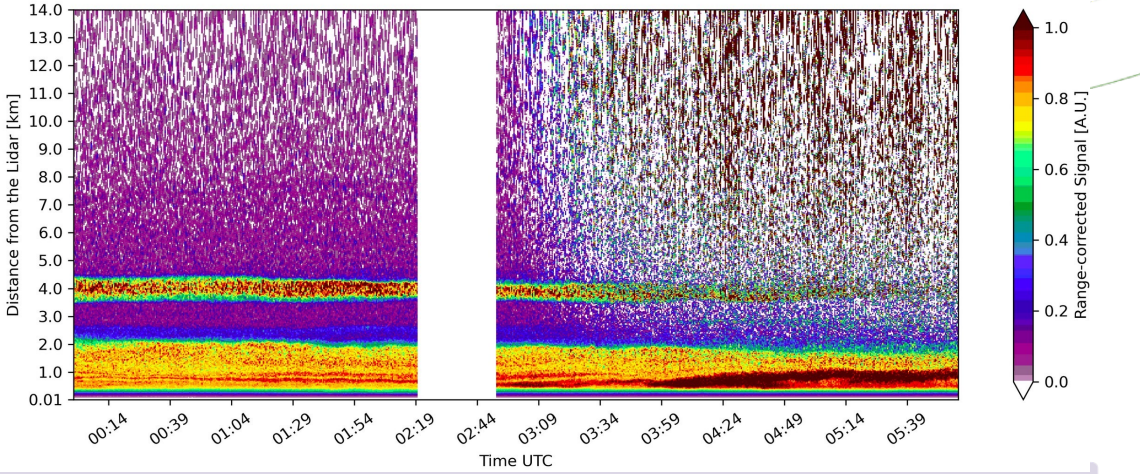


Some critical issues

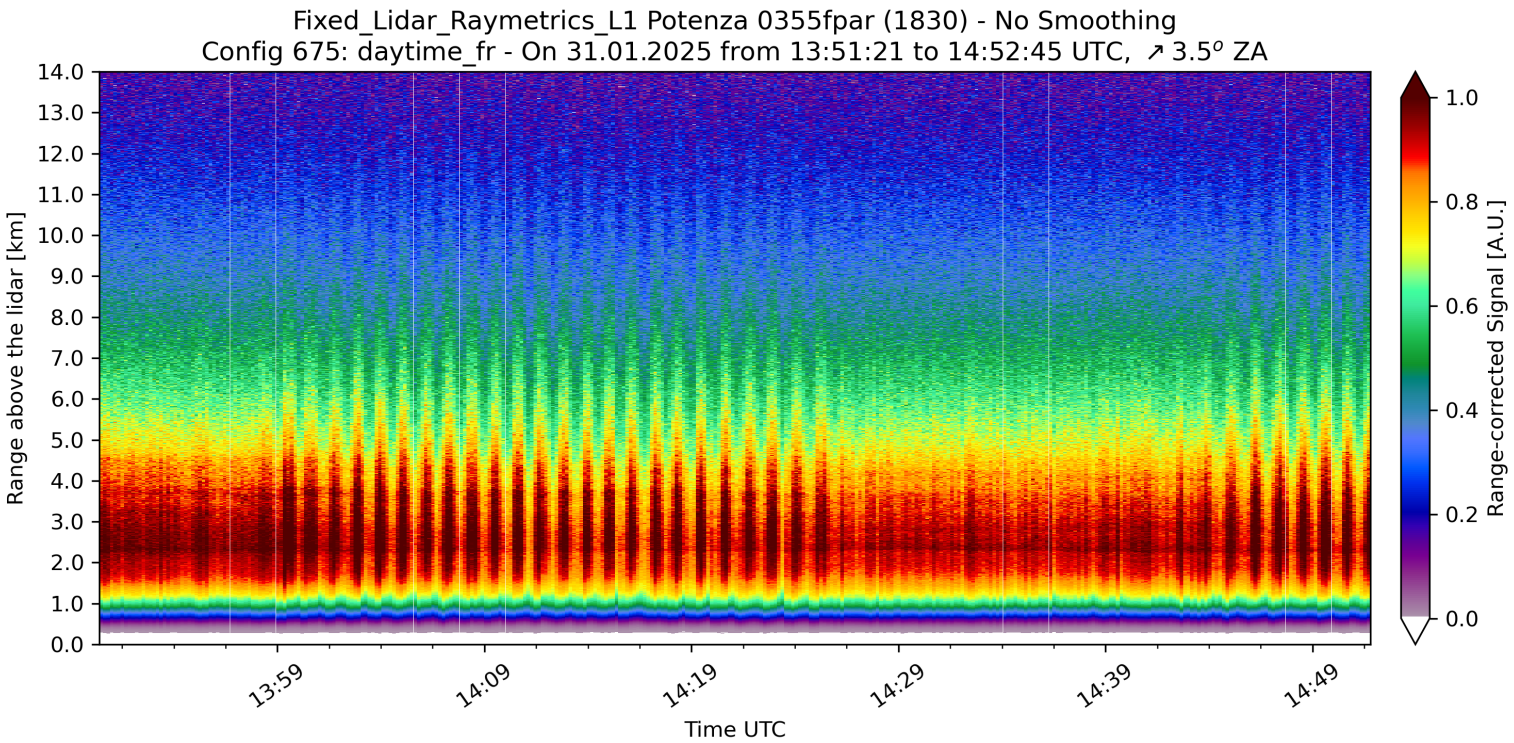
Clouds and Condensation



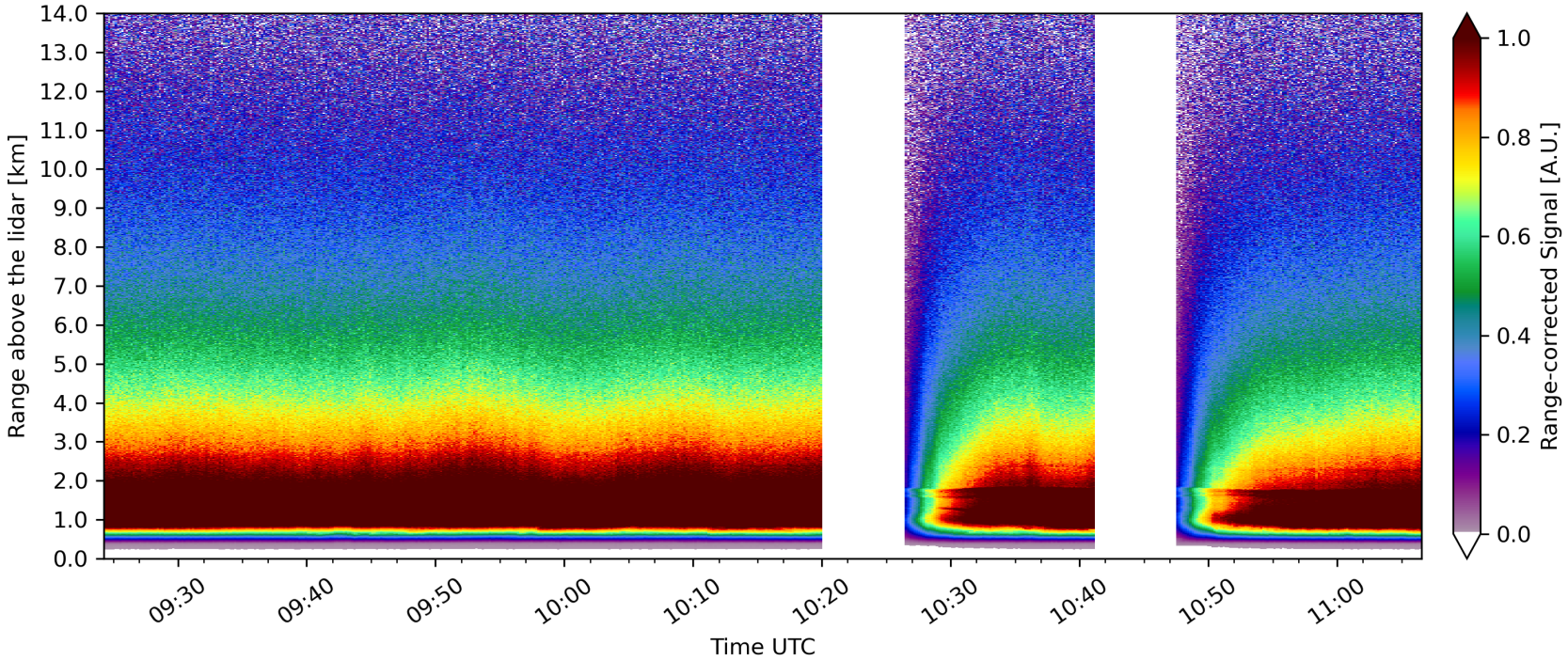
Nighttime but daylight during the measuremnts



With 10sec/profile irregularity otherwise smoothed can be evidenced

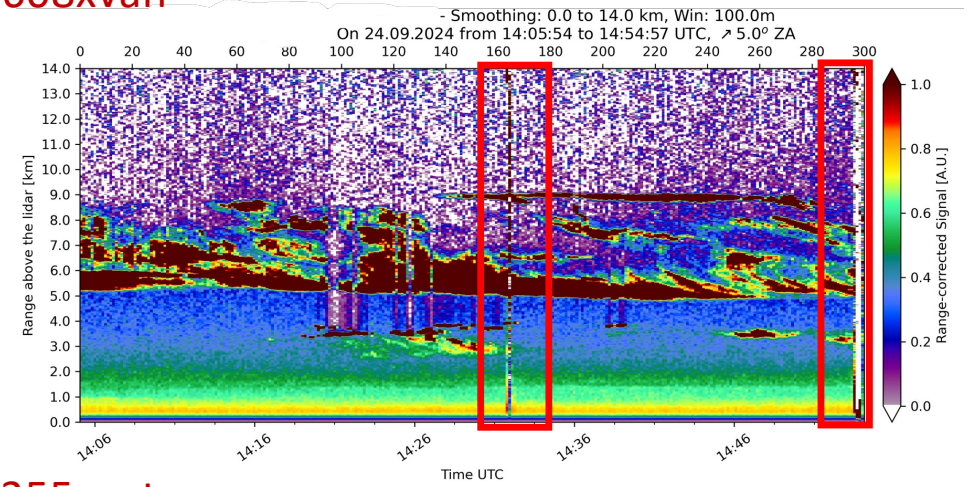


Laser stops and starts without wait the warmup time

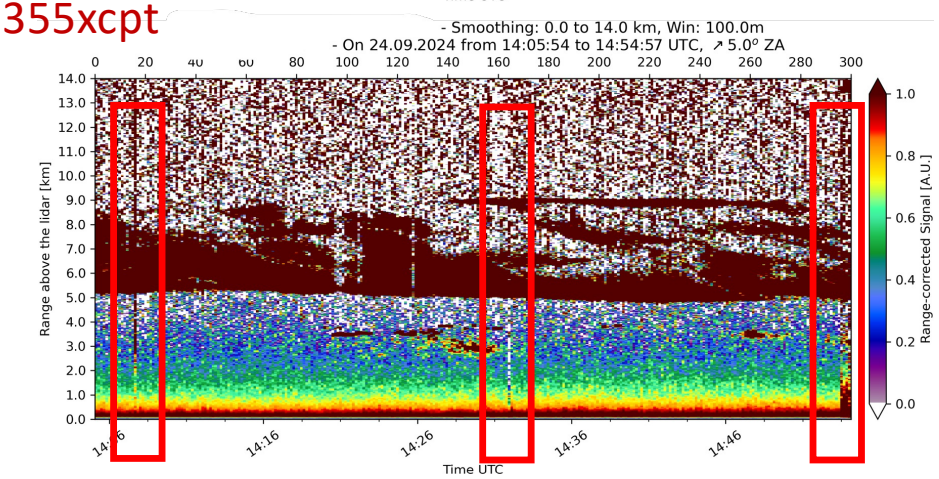


Signal distortions and interspersions

608xvan



355xcpt

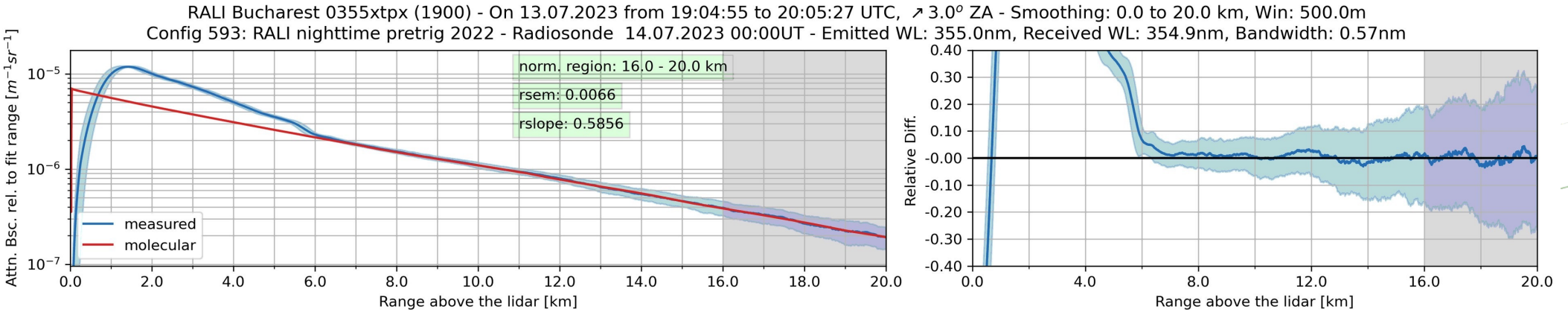


➔ Interspersions by Walky-Talky and strong external power supply, electric interferences

From Michael Haimerl presentation, ACTRIS Week 2024, CARS-ARES Workshop

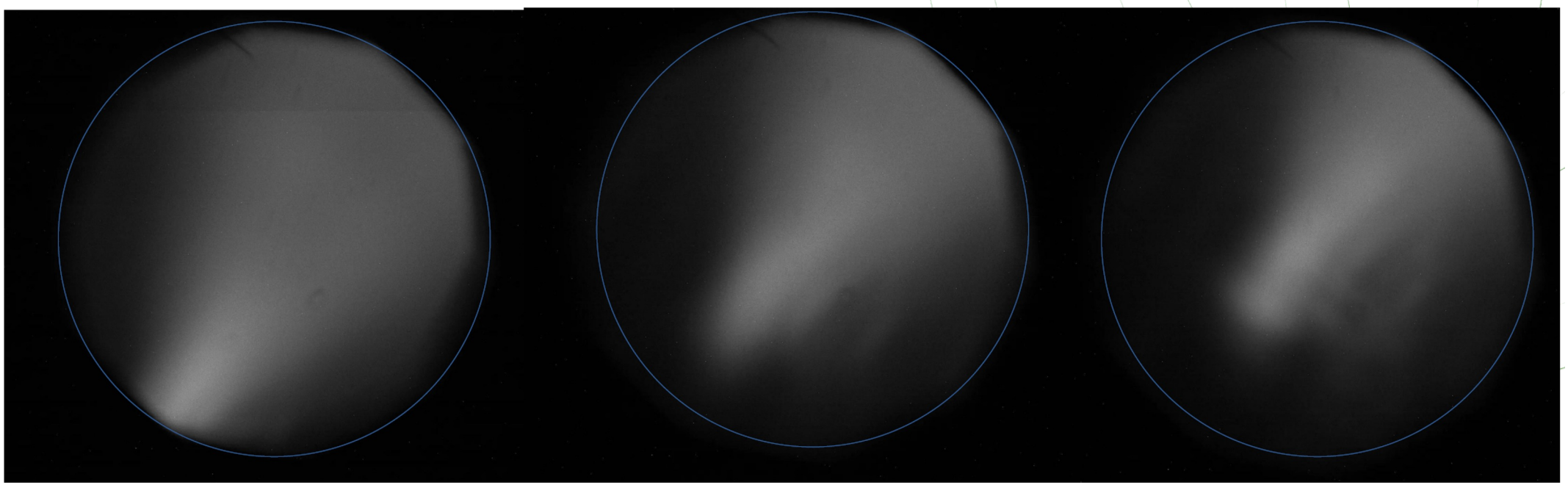
Rayleigh fit test:

- How does a well-aligned case looks like?



laser-telescope alignment in the far range

Channel 532 nm of EMORAL: laser beam alignment

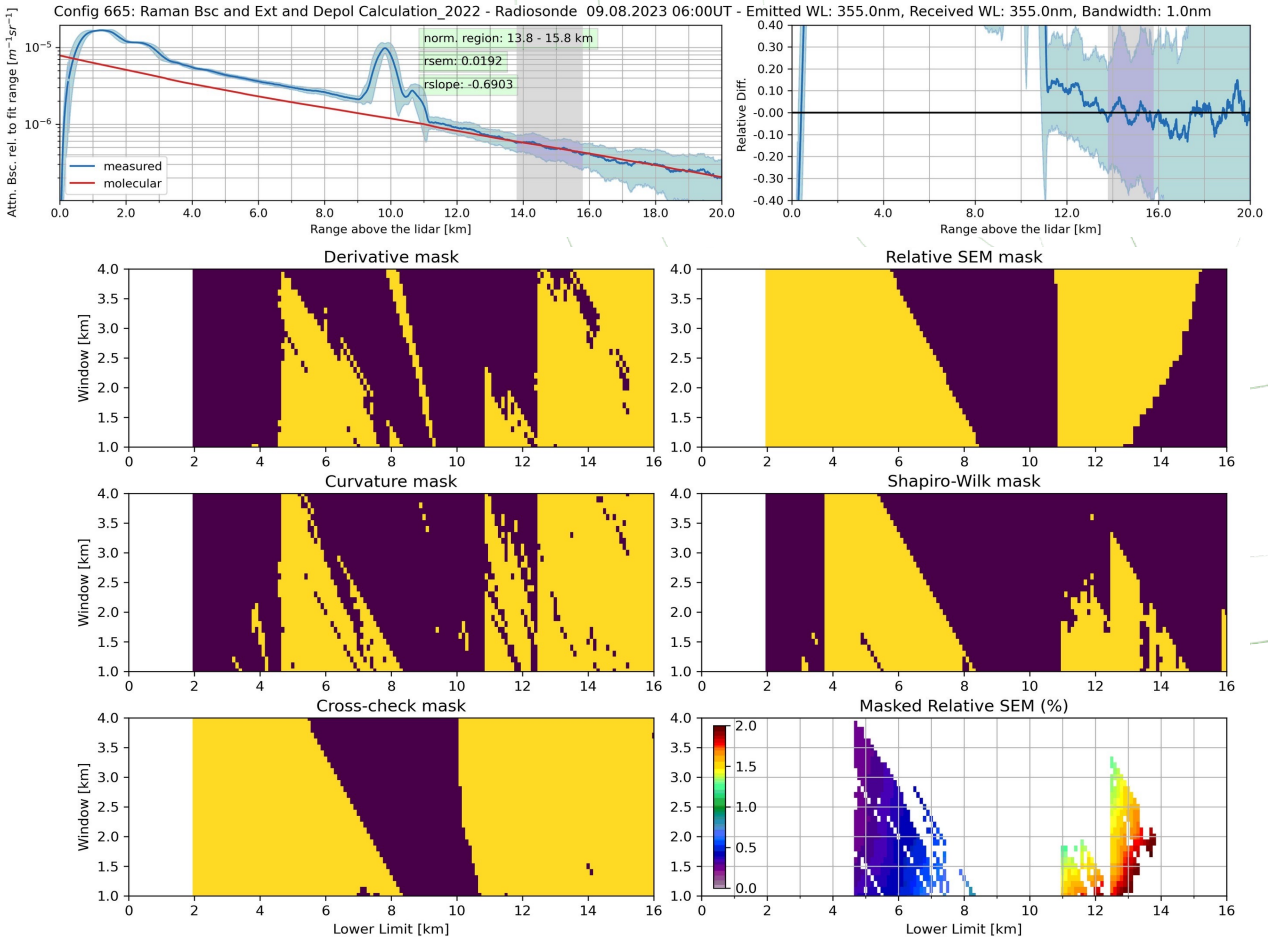


misaligned | alignment by means of an adapted alignment camera | aligned for opt. near range | aligned with tolerance

see: ACTRIS – CARS webinar 07.02.23 Volker Freudenthaler, QA/QC test measurements

Rayleigh fit test:

- Molecular mask - statistical checks
  - Derivative
  - SEM
  - Curvature
  - Shapiro-Wilk
  - Cross-check



THANKS!

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